

Human-rated Safety Certification of a High Voltage Robonaut Lithium-ion Battery



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Introduction



Brief description of Mission
Characteristics of cell and battery
Process used for certification
Details of test process
Details of Qualification and
Flight Acceptance Testing



Mission Objectives

- Intention of eventually taking over tasks too dangerous or mundane for astronauts.
 - Holding still and not breathing are excellent attributes of R2
 - Can handle a wide-range of EVA tools and interfaces
 - Same tools that astronauts currently use and eliminates the need for specialized tools just for robots.
 - Speed at which it works is four times faster than the first version (R1)
 - R2 more dexterous and has deeper and wider range of sensing.
 - Advanced technology spans the entire R2 system and includes: optimized overlapping dual arm dexterous workspace, series elastic joint technology, extended finger and thumb travel, miniaturized 6-axis load cells, redundant force sensing, ultra-high speed joint controllers, extreme neck travel, and high resolution camera and IR systems.
 - Significant Benefit for Robotic precursor missions.
 - R2 would bring one set of tools such as setup and geologic investigations.
- Collaboration with GM
 - Highly dexterous anthropomorphic capability needed for automated automotive manufacturers



Cell and Battery Characteristics



Robonaut battery characteristics

- 91 V / 63 Ah nominal (105 to 68.75 V)
- 5.3 Ah Boston Power lithium-ion cells
- 12 P 25S
- 12P (virtual cell or module) config. gives the required capacity
- 12P5S forms a single cartridge and 6 of those cartridges are further tied in series to provide the required voltage.





Cell Characteristics

Specifications



Certifications

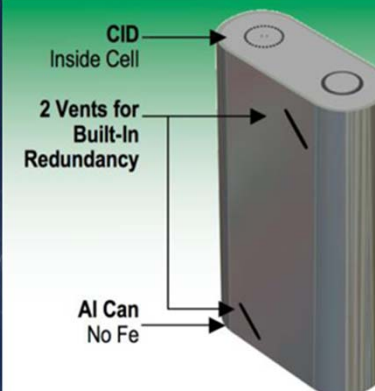
UN 38.3, UL1642, IEC 62133, ROHS 2002/95/EC
In Process: Nordic Ecolabel

Cycle Life at 100% Depth of Discharge (DOD)

Nominal capacity ¹	5300 mAh
Nominal energy ¹	19.3 Wh
Nominal voltage	3.65 V
Energy density	Gravimetric 207 Wh/kg Volumetric 490 Wh/L
Nominal cell impedance	15.5 mΩ
Cycle life (1C discharge at 23°C)	100% DOD >1000 cycles 90% DOD >2000 cycles 80% DOD >3000 cycles
Max continuous discharge rate (0 -100% SOC)	13 A
Allowable 10s pulse capability ²	1000 W/kg
Standard charging method	Constant current (CC) 3.7A (0.7C) to 4.2V Constant voltage (CV) 4.2V to 50 mA
Max charge rate (continuous)	10.6 A
Nominal cell weight	93.5 g
Operating Temperature	Charge -20 to +60 °C Discharge -40 to +70 °C
Storage Temperature	-40 to +60 °C

¹ Standard discharge 0.2C to 2.75 V
² 50% to 100% SOC

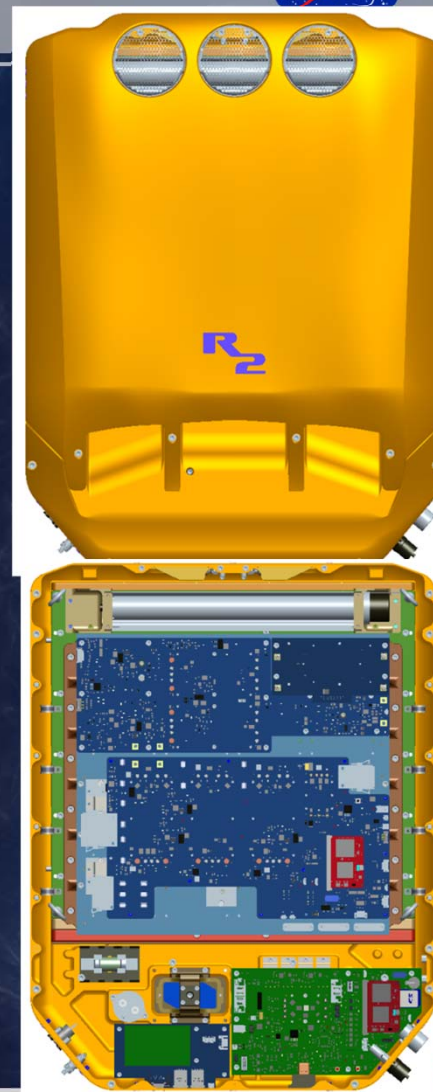
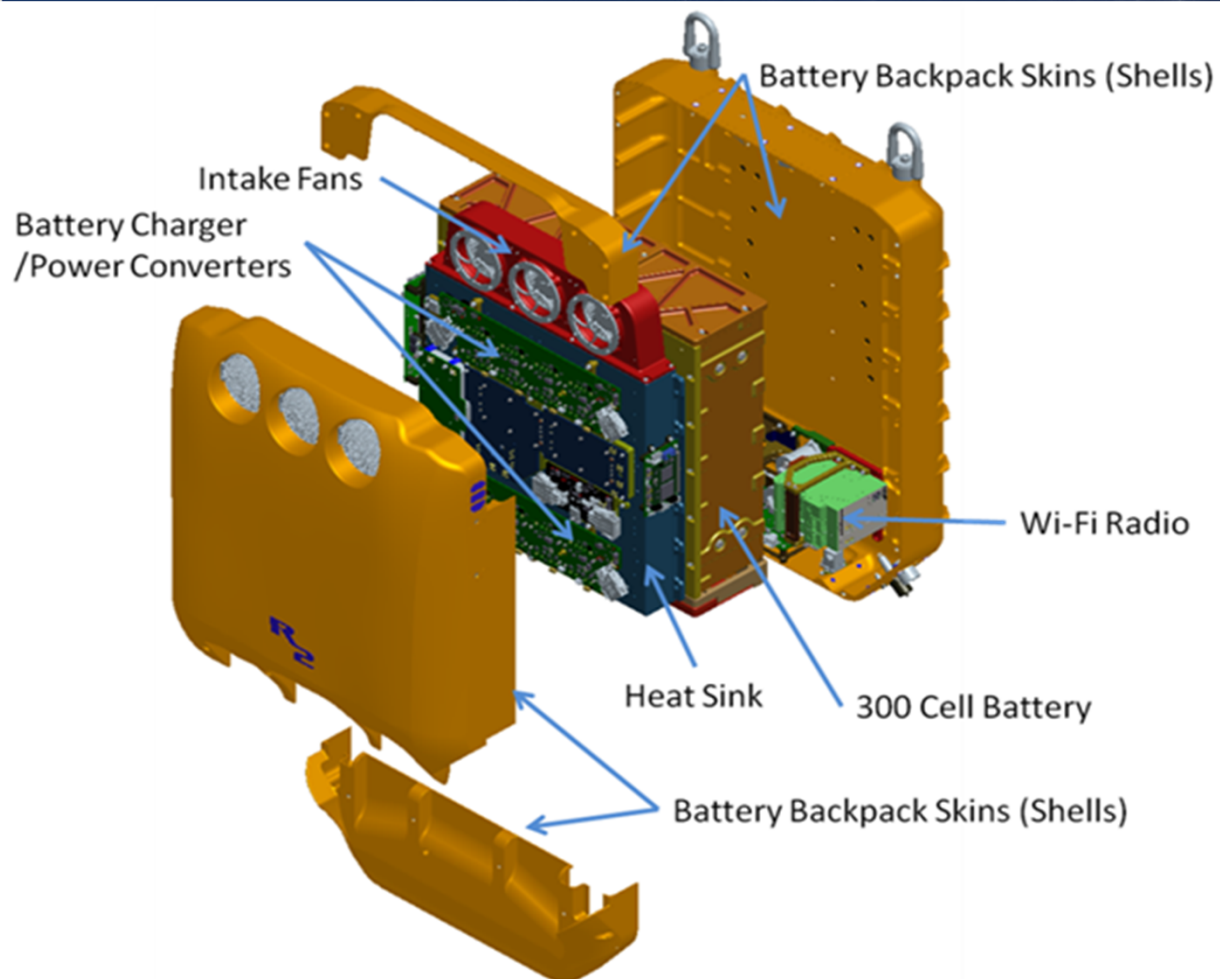
Swing Safety Components



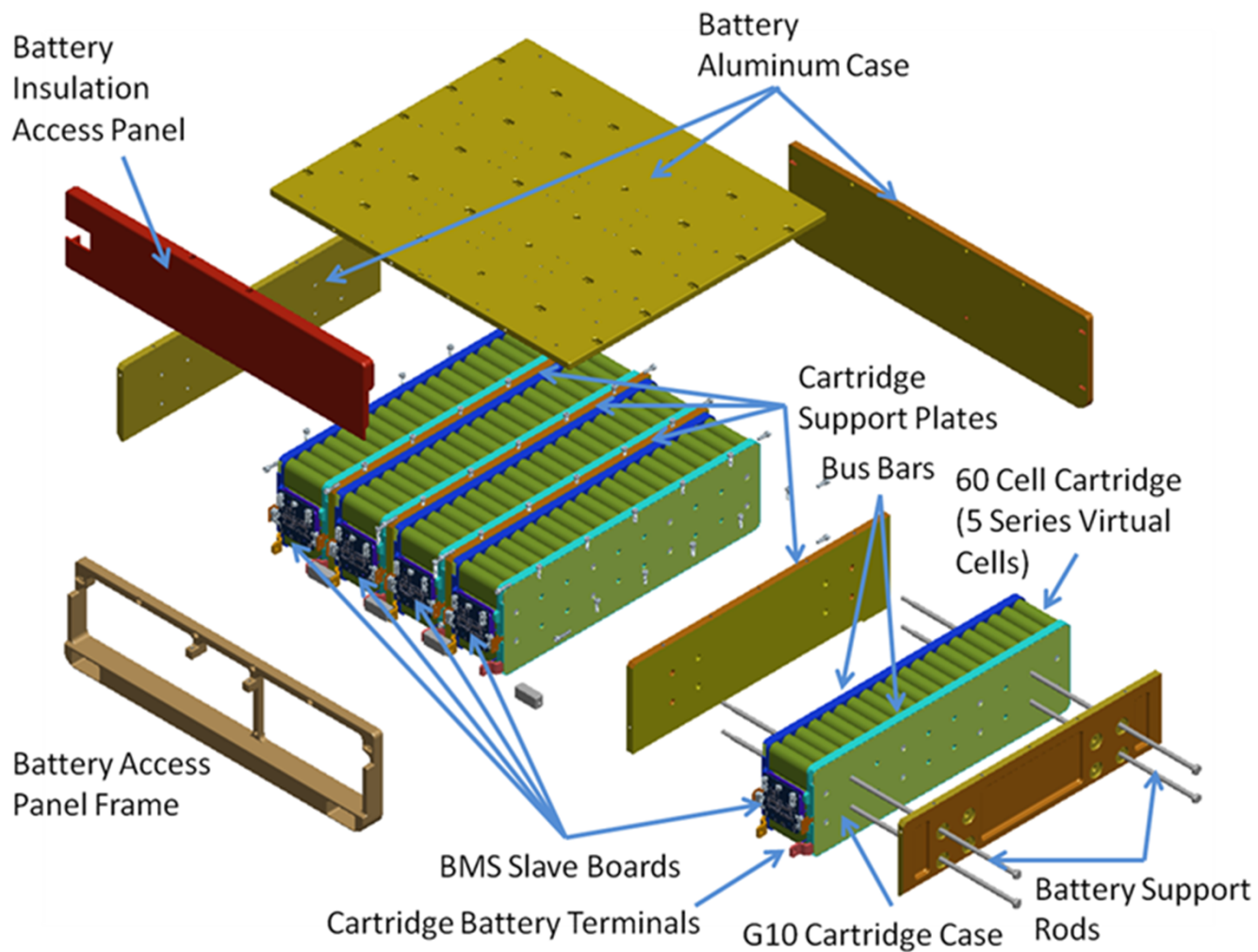
http://www.boston-power.com/sites/default/files/documents/940-0013-001_Swing_5300_DS_Rev_001_0.pdf



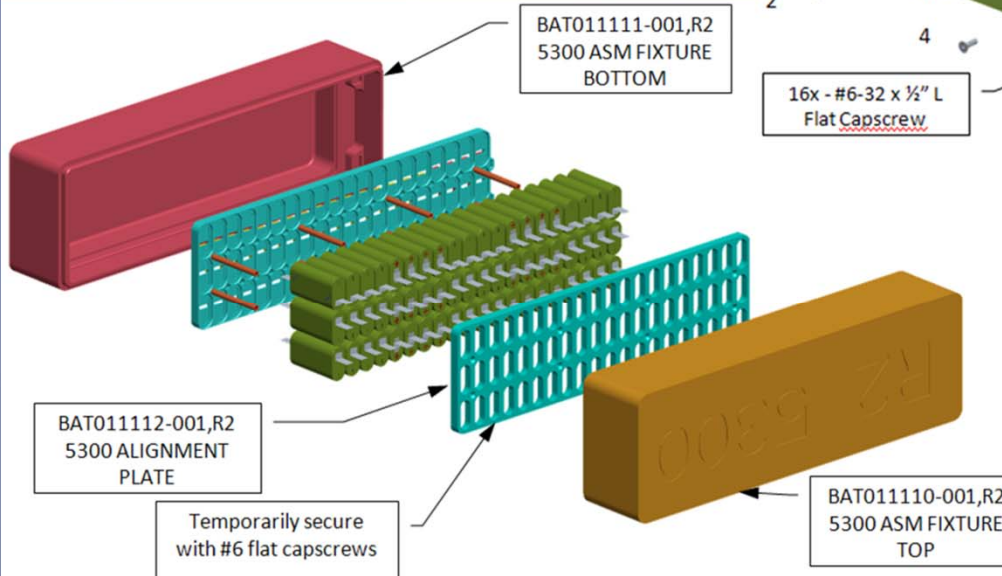
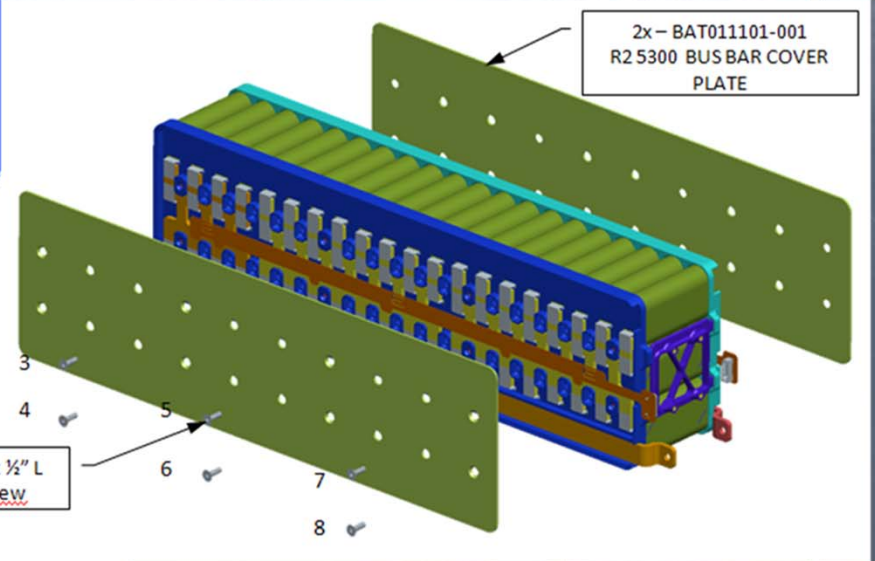
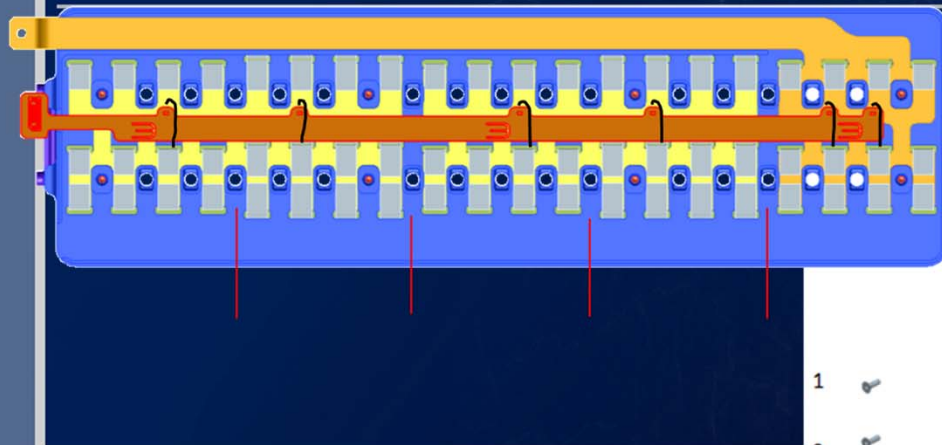
Robonaut Backpack



Expanded View of R2 Battery Pack

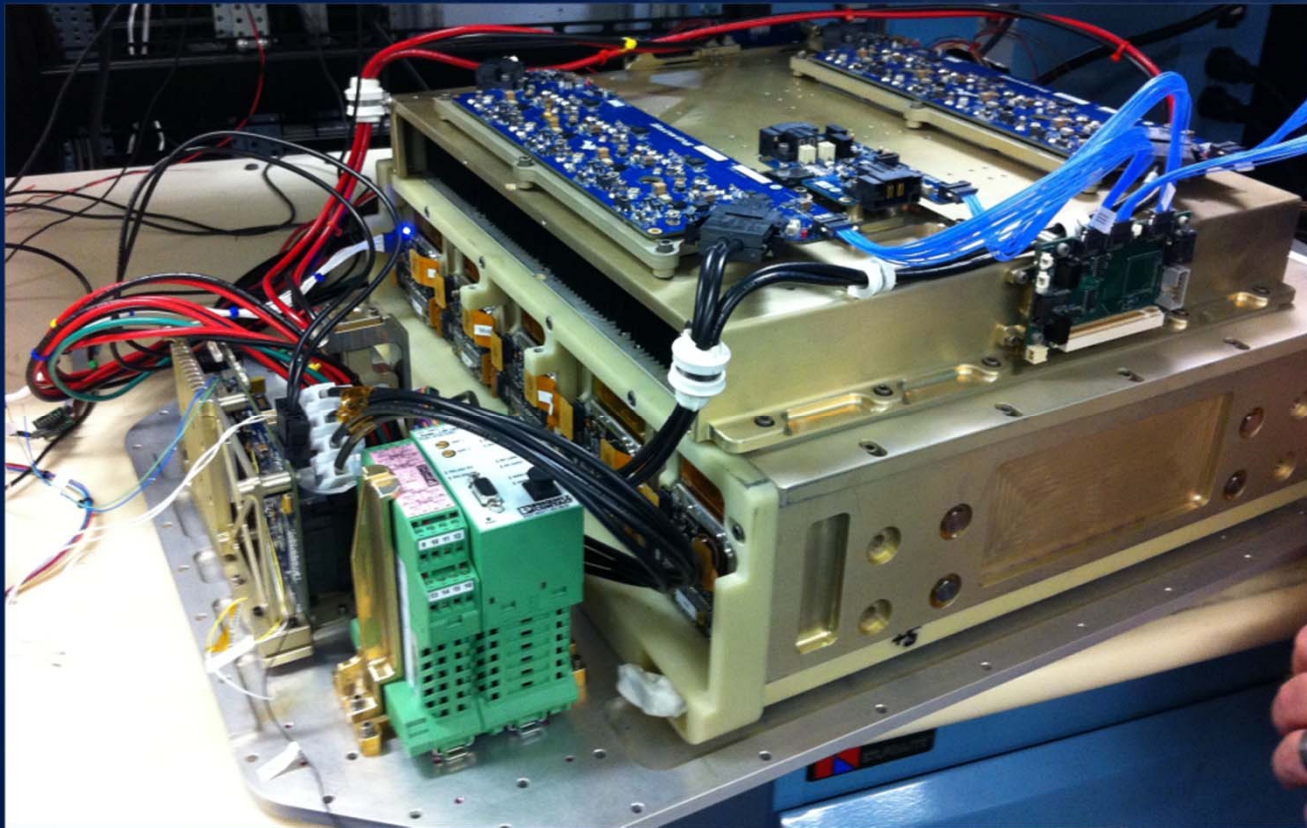


R2 Battery





Working Model of R2 Battery



Battery Management System Characteristics



BMS Slave Board

- Configurable to up to 12 series cells
- Stackable up to 31 boards (372 series cells)
- Over/Under Voltage Hardware Comparators
- Over Temp Hardware Comparators
- Voltage and Temperature Monitoring
- All hardware safeties trip an interlock signal which can be used by the master as a hardware inhibit

BMS Master Board

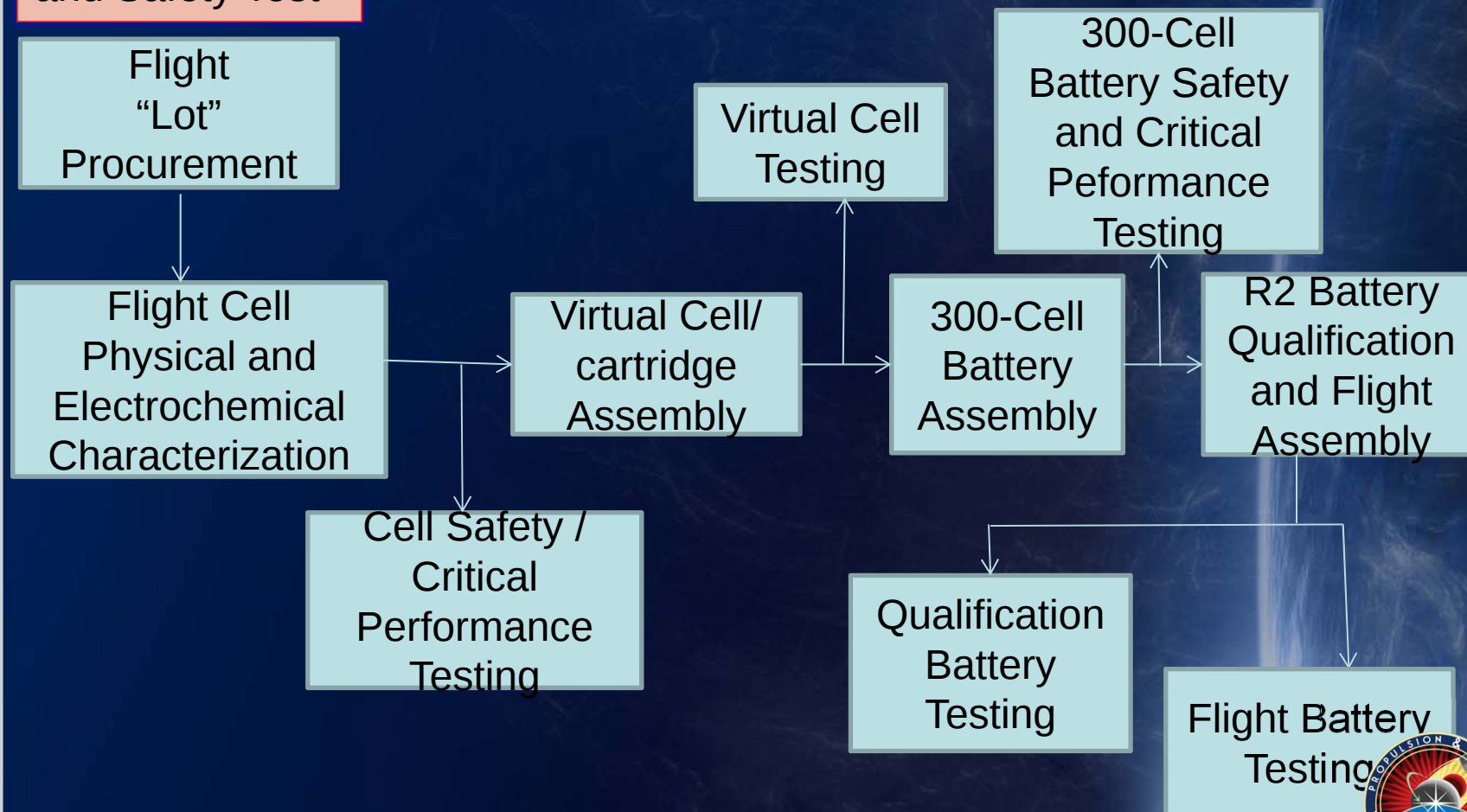
- Communicates with slave boards via i2c interface
- Independent stack level Over/Under voltage monitoring
- Over Current Monitoring
- Disengages battery from system during any safety event



Flow Diagram for Flight Certification



- Cell Selection
- Performance and Safety Test



Cell Selection



- Cell chosen by hardware owner to meet high energy and high power ; Space Act Agreement with Boston Power
- Single Cell and Virtual Cell Engineering Tests performed – cell found suitable for application; single cell and virtual cell module safety understood very well
- Cell manufacturing facility audit conducted (traceability to each cell is provided by cell manufacturer)
- New “flight lot” of cells purchased



Cell / Virtual Cell / Battery Tests



Cell Tests

1. **Physical** (dimension, mass, visual) and **Electrochemical** characterization (including dc resistance and charge/discharge cycles)
2. **Safety tests** (minimum 3 cells for each test; worst case indicated)
 - 2a. **Overcharge** : 1C rate
 - 2b. **Overdischarge**: 1C rate
 - 2c. **External short**: 10 mohms
 - 2d. **Heat-to-vent**: up to 200 °C if venting does not occur before that temp.
 - 2e. **Vent and burst pressure test**

Virtual Cell Tests

1. **Physical** (dimension, mass, visual) and **Electrochemical** characterization (including dc resistance and charge/discharge cycles)
2. **Safety tests**
 - 2a. **Overcharge** : 12 A rate
 - 2b. **Overdischarge**: 1C rate (63.6 A)
 - 2c. **External short**: <1 mohms

Battery Level Tests

1. **Physical** (dimension, mass, visual) and **Electrochemical** characterization (including dc resistance and charge/discharge cycles)
2. **Safety tests**
 - Battery Hardware controls (with battery simulator)
 - Battery Software controls (with battery simulator)
 - Battery High Voltage and Shock Prevention Inspections
 - Battery overcharge
 - Battery overdischarge
 - Battery external short (< 5 mohms)



Battery Design Optimizations

- Cell screening, matching
- Cell thermal analysis and optimum heat dissipation and thermal sensors design
- Virtual cell isolations
- Active balancing
- Circuit board optimizations – suitable components
- Cartridge and Battery structural optimizations
- Software and hardware control in-house design optimization, build and testing
- Stringent testing to confirm design under nominal and off-nominal conditions.

Battery Safety Controls

Overcharge:

- 2 Virtual Cell voltage monitoring and controls for overvoltage
- 1 Battery voltage monitoring and control for battery overvoltage
- Temperature monitoring and control
- (One relay and two FETs; redundant set; slave boards monitor and report to Master that controls the relay and FETs)

Overdischarge :

- 2 Virtual cell voltage monitoring and control for undervoltage
- 1 Battery voltage monitoring and control for undervoltage
- Temperature monitoring and control

Battery Safety Controls

External Short:

- Fuse at Battery level; Fuse at cartridge level
- PTC fuses on each sense line
- BMS current control
- Temperature monitoring and control
- At least two layers of insulation between virtual cells
- Battery box provides physical isolation between cartridges
- Conformal coating, Wiring insulation, proper wire routing, inspection and test, insulation resistance measurements; Circuit board has air gap between electronics and cell modules

Internal Short:

- Cell manufacturing facility Audit
- Cell screening with sample cell CT scan and DPA
- Cell selection and matching with stringent criteria
- Vibration screening of flight batteries
- Used well within manufacturer's specification
- Thermal analysis to provide for good heat dissipation

Battery Qualification Tests



1. **Physical** (dimension, mass, visual) and **Electrochemical** characterization (including OCV, dc resistance and charge/discharge cycles)
2. **Thermal Characterization** (50 °F, 70 °F and 90 °F)

Charge /discharge capacity checks carried out before and after tests 3 and 4.

3. **Qualification Vibration**

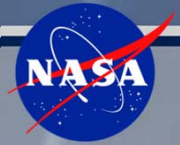
Frequency (Hz)	ASD (G^2 / Hz)	dB/Oct	G_{RMS}
20.0	0.0250	*	*
80.0	0.1000	3.01	1.94
350.0	0.1000	0.00	5.55
2000.0	0.0175	-3.01	9.58

4. **Vacuum Leak Check**
~0.1 psi for 6 hours

Pass/fail criteria: <0.1 % OCV; < 1% capacity for both 3 and 4.

5. **Power Quality Testing**
6. **EMI Testing**
7. **Joint Station LAN Testing**





Battery Flight Acceptance Tests

1. **Cell Screening and Matching** (OCV, mass, dimensions, dc resistance and capacity – 6 sigma range; OCV matched to less than 0.1 %; dc resistance within 5%; capacity within 1 %); cells have been found to exceed requirements with tight match for the flight lot.
2. **Virtual Cell / Cartridge / Battery Assembly**
3. **Battery Physical** (dimension, mass, visual) and **Electrochemical** characterization (including OCV, dc resistance and charge/discharge cycles)

Charge /discharge capacity checks carried out before and after tests 3 and 4. Second discharge capacity used for pass/fail criteria.

4. Vibration:

Frequency (Hz)	ASD (G^2 / Hz)	dB/Oct	G_{RMS}
20.0	0.0100	*	*
80.0	0.0400	3.01	1.22
350.0	0.0400	0.00	3.51
2000.0	0.0070	-3.01	6.06

5. Vacuum Leak Check ~0.1 psi for 6 hours

Pass/fail criteria: <0.1 % OCV; < 1% capacity for 3 and 4.

6. Acoustic Testing with charge/discharge/charge cycles.



Summary



- NASA's rigorous certification process is being followed for the R2 high voltage battery program for use of R2 on International Space Station (ISS).
- Rigorous development testing at appropriate levels to credible off-nominal conditions and review of test data led to design improvements for safety at the virtual cell, cartridge and battery levels
- Tests were carried out at all levels to confirm that both hardware and software controls work.
- Stringent flight acceptance testing of the flight battery will be completed before launch for mission use on ISS.

